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Validation and Application of Models to Predict Facemask Influenza Contamination in Healthcare Settings

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Abstract

Facemasks are part of the hierarchy of interventions used to reduce the transmission of respiratory pathogens by providing a barrier. Two types of facemasks used by healthcare workers are N95 filtering facepiece respirators (FFRs) and surgical masks (SMs). These can become contaminated with respiratory pathogens during use, thus serving as potential sources for transmission. However, because of the lack of field studies, the hazard associated with pathogen-exposed facemasks is unknown. A mathematical model was used to calculate the potential influenza contamination of facemasks from aerosol sources in various exposure scenarios. The aerosol model was validated with data from previous laboratory studies using facemasks mounted on headforms in a simulated healthcare room. The model was then used to estimate facemask contamination levels in three scenarios generated with input parameters from the literature. A second model estimated facemask contamination from a cough. It was determined that contamination levels from a single cough (≈ 19 viruses) were much less than likely levels from aerosols (4,473 viruses on FFRs and 3,476 viruses on SMs). For aerosol contamination, a range of input values from the literature resulted in wide variation in estimated facemask contamination levels (13–202,549 viruses), depending on the values selected. Overall, these models and estimates for facemask contamination levels can be used to inform infection control practice and research related to the development of better facemasks, to characterize airborne contamination levels, and to assist in assessment of risk from reaerosolization and fomite transfer because of handling and reuse of contaminated facemasks.

Keywords

Contamination; influenza; surgical masks

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1. INTRODUCTION

Facemasks, including National Institute for Occupational Safety and Health (NIOSH)-certified N95 filtering facepiece respirators (FFRs) and surgical masks (SMs), are nonpharmaceutical interventions used to reduce the transmission of respiratory pathogens. The designed and intended uses of FFRs and SMs differ in the types of protection provided. FFRs are typically composed of electret filter media and seal tightly to the face of the wearer, whereas SMs are generally loose fitting and may or may not contain electret filtering media. FFRs are designed and worn to reduce the wearer's inhalation exposure to infectious particles. The Centers for Disease Control and Prevention (CDC) recommends that health-care workers (HCWs) use fit-tested FFRs when in close contact with patients infected with a respiratory pathogen that spreads via aerosol transmission, such as *Mycobacterium tuberculosis*.⁽¹⁾ Similar recommendations have been made for respiratory pathogen outbreaks, such as the 2009 H1N1 influenza pandemic, in which aerosol transmission was considered likely.^(2,3) SMs reduce contamination of the environment from particles generated by the wearer and provide a barrier to protect HCWs from splashes and sprays of body fluids such as blood. Both FFRs and SMs restrict users from touching their mouth and nose, which limits opportunities for contact transmission of respiratory pathogens from the hands to the mucosa of the wearer. Studies in various workplaces have demonstrated that fit-tested FFRs, when used in a complete respiratory protection program, are effective at reducing inhalation exposures,^(4–9) whereas SMs are far less effective for this purpose because of their poorer fit and filtration performance.^(10–12) Laboratory studies have demonstrated the superior filter performance of FFRs over SMs by using various simulants for respiratory pathogens.^(13–16)

As with many other interventions (such as hand washing and vaccination), the effectiveness of FFRs at reducing human-to-human transmission of respiratory pathogens is ultimately governed by compliance. Adherence to proper FFR use practices requires careful attention to all elements of a respiratory protection program, including training, fit-testing, and proper donning/doffing technique. Previous study findings on HCW adherence to proper respirator use suggest that compliance is often lacking.^(17–19) Another challenge with FFRs is that proper technique is required to put them on and take them off. Poor doffing techniques can lead to the transfer of infectious material to the user's hands.⁽²⁰⁾ Concerns about contaminated FFRs contributing to disease transmission (e.g., as fomites) are fairly unique to healthcare and emergency response settings, in which the respirator is used to reduce exposures to an infectious aerosol that can also cause infection via contact transmission. Most particulate hazards, common to other occupational sectors where FFRs are used, such as machine shops, construction sites, and other industrial facilities, are noninfectious inhalation hazards.

Even within healthcare, the risks of handling a contaminated FFR are complex. Unlike most other medical and personal protective devices, FFR and SM contamination is affected by the user's breathing, which causes nearby particles in the air to come in contact with the facemask. For most noninvasive medical devices (such as stethoscopes) and other types of nonrespiratory personal protective equipment (gloves, lab coats, and eyewear), contamination occurs via contact, direct sprays or splashes (from a cough or sneeze, for

example), and settling forces. The electret filter medium used in an FFR consists of several layers of air-permeable nonwoven fibers. Thus, contamination occurs not only at the surface of the FFR but also throughout the depths of the fiber bed within each layer. Laboratory studies that have evaluated layer-by-layer deposition have found that aerosolized virus is mainly deposited in the middle layers, but deposition also depends on the size and composition of the aerosol.^(10,21)

To address concerns raised by HCWs and to improve compliance with proper respirator use, NIOSH, the Department of Veterans Affairs (VA), and other researchers have proposed developing a “B95” respirator specific for HCWs, as part of project BREATHE (Better Respiratory Equipment using Advanced Technologies for Healthcare Employees).⁽²²⁾ The first draft of the requirements for a proposed B95 respirator describes 28 characteristics, including several that focus on the desire to minimize transfer of infectious respiratory pathogens from a contaminated respirator to the hands of the wearer. The authors of that report recognized that no respirator on the market today could meet all 28 requirements, and thus prioritization would enable technologists and manufacturers to focus on those characteristics that impact HCWs the most. Unfortunately, few data on FFR contamination are available to assist with such prioritization. For example, if actual FFR contamination levels are small enough that transfer to the mucosa of the wearer is unlikely (that is, if FFRs are not an important fomite concern), then this would suggest that these characteristics should be given lower priority than other characteristics such as fit and comfort.

There are other applications for which information about facemask contamination levels are important. For example, FFR reuse and extended use have been proposed as possible ways to maintain respirator supplies during a pandemic.^(23,24) With the current threat of the newly identified influenza H7N9 in China,^(25,26) concerns over facemask availability, particularly FFRs, have again come to the forefront of pandemic preparedness planning. FFR reuse would allow the HCW to don and doff the same FFR multiple times, and extended use would allow a HCW to wear one FFR for encounters with multiple patients. One possible FFR reuse strategy that has been studied extensively is to employ a biological decontamination method to kill or inactivate trapped respiratory pathogens.^(21,27–35) To accurately characterize the risks of FFR reuse and extended use and to develop test methods to quantify decontamination performance, FFR contamination levels need to be estimated or measured. In the absence of this information, other considerations are used. For example, ASTM test methods E2720-10 and E2721-10 set FFR contamination level targets based upon the detection limits of the assay, rather than on the likelihood that these FFR contamination levels are possible.^(36,37) FFR contamination levels are critical to understanding the threat of reaerosolization of infectious particles from an FFR. Fisher *et al.* found that the percentage of viruses reaerosolized was dependent upon the type and amount of FFR contamination.⁽³⁸⁾ The authors based their experiments on the detection limits of the assay, similar to ASTM methods E2720 and E2721.

Surprisingly few experimental data on facemask contamination levels are available from hospital settings, despite the increase in facemask research. In many situations for which there are no experimental data, models can be used. For example, a population transmission model has been used to explore the impact of population-wide facemask use,⁽³⁹⁾ and other

studies have evaluated models describing influenza transmission, effectiveness of interventions, and risk.^(40–46)

In our study, the mathematical model used previously by Fisher *et al.* for assessing risks because of reaerosolization of viruses was used to calculate the potential influenza contamination of facemasks from aerosol sources for a variety of healthcare settings.⁽³⁸⁾ The aerosol model was validated with previously collected data from laboratory studies in which face-masks were mounted on headforms in a simulated healthcare room. The model was then used to estimate facemask contamination levels for three scenarios generated with input parameters derived from the literature. A second model is also presented, which estimates facemask contamination from direct-spray sources. Results from the two models are compared.

2. METHODS

2.1. Literature Search Strategy for Model Inputs

We searched via PubMed and Google Scholar for publications on the major topic headings: aerosol and influenza and qPCR (quantitative real-time polymerase chain reaction); aerosol and influenza and concentration; duration of provider-patient interaction; duration of physician-patient interaction; duration of nurse-patient interaction; workplace protection factor (WPF); breathing rate; and HCW breathing rate. References were obtained and reviewed for relevance. Because not all relevant publications are available through the chosen publication databases, references cited within relevant manuscripts were also reviewed for relevance and selected for additional scrutiny as necessary. Similarly, technical specifications and test standard documents relevant to facemasks were also considered.

2.2. Facemask Contamination Models

In this work, two models were used to estimate facemask contamination. These models consider contamination only via deposition of aerosols or direct sprays (such as cough) that come in contact with the facemask; they do not consider other sources of contamination, such as any virus that gets transferred to the facemask from the hands. A list of parameters for the model equations is provided in Table I. Equation (1) is the model used to estimate facemask contamination from aerosols (C_{fa}). This model calculates C_{fa} from airborne influenza virus concentration (C_{out} , virus/m³) and facemask use factors such as facemask user inhalation rate (IR_a , m³/hour), duration (t , hour) of facemask use (length of patient interaction), and facemask virus barrier efficiency (E_b):

$$C_{fa} = C_{out} \times IR_a \times E_b \times t. \quad (1)$$

E_b is the ratio of virus in the inspiratory volume of air that is captured by the facemask and can be determined by using Equation (2), where C_{in} is the concentration of virus inside the facemask and C_{out} is the concentration of virus outside the facemask in the breathing zone of the wearer:

$$E_b = 1 - \frac{C_{in}}{C_{out}} \quad (2)$$

Equation (3) is the model for estimating face-mask contamination (C_{fc}) via direct spray produced by a cough:

$$C_{fc} = V_c \times \frac{A_{fm}}{A_c} \quad (3)$$

In this model, V_c is the number of viruses in a cough, A_{fm} is the area of a facemask, and A_c is the area of the cough at the distance between the cougher and the HCW. This equation was adapted from a risk analysis by Nicas and Jones.⁽⁴³⁾

2.3. Facemask Contamination Model Validation

The aerosol model (Equation (1)) was validated with use of a 795-ft³ simulated patient examination room. A detailed description of the simulated patient room can be found elsewhere.⁽¹⁰⁾ A total of nine data points were used to validate Equation (1). Four of the data points were derived from the results reported by Noti *et al.*⁽¹⁰⁾ The other five data points were collected as part of experiments designed to investigate the effect of influenza aerosol concentration on facemask contamination, which is the subject of a separate manuscript in preparation (J. D. Noti, personal communication). For completeness, a short description will be given here. A coughing simulator was used to expel H1N1 influenza strain A/WS/33 into the 3.2 m × 3.2 m × 2.3 m chamber. Virus aerosol concentration was measured beside the mouth and inside of the facemask of a breathing headform with a previously described NIOSH aerosol sampler and used in Equations (1) and (2) for C_{out} and C_{in} , respectively.^(47–49) The breathing headform, positioned 2 m away from the coughing simulator, was attached to a breathing simulator and maintained at a rate (IR_a) of 1.92 m³/hour. The breathing headform was fitted with an FFR or SM in sealed and unsealed configurations. An FFR or SM was attached to the headform using a silicone sealant or fitted on the headform using the tethering straps of the facemask to provide both sealed and unsealed conditions, respectively.⁽¹⁰⁾ The E_b of the facemasks was determined for SMs and FFRs in sealed and unsealed conditions using Equation (2). Table II lists the input values for the variables in Equation (1) used to calculate C_{fa} . Virus captured by the facemask was recovered from 5 cm² coupons excised from the FFR or SM and quantitated by qPCR. Given the coupon sampled was 5 cm² of an approximate 200 cm² face-mask, the number of viruses detected on the coupon by qPCR was multiplied by 40 to give a total number of viruses on the facemask assuming equal deposition of virus across the surface of the facemask. This value was compared to the predicted value. Unfortunately, no data are available to validate the model described in Equation (2) to estimate FFR contamination by a direct spray from cough or sneeze.

2.4. Experimental Design: Application of the Models

To better understand how the input parameters affect estimated facemask contamination levels, Equation (1) was applied for three scenarios (termed “low,” “high,” and “likely”) designed to span the gamut of situations that a facemask would be used in a typical healthcare setting. These calculations were done for both an FFR and an SM. Published data were used to obtain low, high, and likely values for C_{out} , IR_a , E_b , and t . Another calculation was performed using Equation (3) to estimate C_{fc} . The input variable V_c was chosen from data found in the peer-reviewed literature,⁽⁵⁰⁾ whereas A_{fm} was estimated from area measurements of facemasks in our laboratory supplies and the value selected for A_c was based upon previous work by Nicas and Jones.⁽⁴³⁾ Because of the paucity of data available related to these input variables, Equation (3) was applied for only a single scenario with use of likely values.

2.5. Data Analysis

A statistical comparison of the laboratory-measured contamination and the estimated FFR contamination was performed with a two-tailed t -test (Microsoft Excel 2010). The correlation curve, correlation equation, and R^2 value were determined with Microsoft Excel (2010).

3. RESULTS

3.1. Literature Review

The PubMed and Google Scholar searches for the major topic headings resulted in 151 citations for peer-reviewed articles. The 151 references were perused for relevant data, preferably from healthcare settings, for the model inputs. Of the 151 references retrieved, 18 provided potential values for the inputs to our models. All potential input data were evaluated to assign low, high, and likely values. Two additional relevant sources were obtained by reviewing references of the original 18 manuscripts. One of these, ISO/TS 16976-1, a technical specification that provides respiratory and metabolic values intended for the preparation of standards for performance requirements, testing, and use of respiratory protective devices, provided the values for inhalation rates. The references used as inputs to the models to calculate C_{fa} and C_{fc} are summarized in Table III.

3.2. Model-Predicted Facemask Contamination for Various Scenarios

Fig. 1 and Table II show the comparison of the predicted and measured facemask contamination values for the validation experiments demonstrated significant ($p < 0.05$) correlation ($R^2 = 0.95$).

Predicted facemask contamination levels from the low, high, and likely simulated aerosol and likely direct spray scenarios based on inputs from the literature can be found in Table IV and Table V, respectively. For the simulated aerosol contamination scenarios, estimated facemask contamination ranged from 19 to 202,549 viruses and from 13 to 182,477 viruses for FFRs and SMs, respectively. The C_{out} , IR_a , and t values were the same for both the SM and FFR contamination calculations, whereas values for E_b were different between the FFR and SM scenarios.

Contamination by droplet spray produced by a direct cough would lead to 19 viruses becoming trapped on the FFR, given a distance of 0.6 m, a concentration of 355 virus/cough, a particle spread of 3,800 cm², and an FFR area of 200 cm². On the basis of assumed equal sizes (A_{fm}) for the SM and the FFR, the cough contamination for an SM would be the same value as for the FFR.

4. DISCUSSION

There are numerous situations, in particular healthcare settings, where information regarding facemask contamination levels is necessary. In the absence of experimental data, ideally collected from actual workplaces, models can serve a useful purpose if properly validated (where possible) and if assumptions are clearly disclosed. In this study, two models were described to estimate facemask contamination from aerosol and direct-spray (cough) sources. These models were then applied to calculate potential face-mask contamination levels in various scenarios representing typical HCW use. We chose to focus on influenza as a target respiratory pathogen because of continued concerns about newly emerging influenza strains (H5N1, H7N9, etc.) and the lack of aerosol data for other respiratory pathogens.

Laboratory data from a simulated patient room were used to validate Equation (1) (see Table II and Fig. 1). The slope of the linear equation of the best fit line is close to 1; however, many factors could account for the deviation. C_{fa} is directly proportional to C_{out} , IR_a , E_r , and t . C_{out} and E_b , although measured during laboratory experiments, are input values that may fluctuate during experimentation. Virus aerosol concentration varies over time and across the volume of a room. Although the C_{out} was measured with aerosol samplers placed right beside the headform, it is expected that the C_{out} directly exposed to the mask is not equivalent to the measured C_{out} , as the model assumes because of the spatial variability of virus concentration.⁽¹⁰⁾ For the laboratory data, E_b are subject to the spatial variations of both C_{in} and C_{out} in Equation (2). Recovery and detection of viruses from facemasks are not 100% efficient. Loss of virus during experimental procedures was not considered when applying the laboratory determined input values into Equation (1); therefore, it is expected that the model predicted C_{fa} would be greater than the laboratory measured C_{fa} .

Facemask contamination was determined with use of FFRs and SMs in sealed and unsealed configurations exposed to various concentrations of aerosols; therefore, the model was validated with a range of values for two of the model inputs (C_{out} and E_b). The other two variables for the aerosol equation, breathing rate (IR_a) and patient interaction time (t), remained unchanged during facemask contamination experiments, and thus the effects of these variables were not determined. However, the product of breathing rate (m³/hour) and patient interaction/facemask use (hour) is volume (m³). An increase in aerosol volume passing through respirator samples has been shown in previous work to increase respirator contamination in a small test chamber.⁽²¹⁾ This is consistent with the aerosol model (Equation (1)), where facemask contamination is directly proportional to each variable.

In application of the aerosol contamination model (Equation (1)) to the three different scenarios, the estimated influenza contamination of an FFR ranged from approximately 19 to 202,549 viruses, whereas the SM contamination ranged from 13 to 182,477 viruses. On

the basis of the most realistic set of input parameters to simulate a typical situation (scenario #3), the aerosol model suggests that an FFR would become contaminated with approximately 3,482 viruses, whereas an SM would contain approximately 2,744 viruses when used by a HCW with direct patient care during flu season. Simulations using the cough model (Equation (2)) suggest that direct spray via coughs (19 viruses) may not cause high levels of contamination, a finding suggesting that aerosol contamination is the most likely source of facemask contamination.

The input level for airborne influenza virus concentration had the largest impact on C_{fa} . The likely virus aerosol concentration used for the input was 12,000 viruses/m³, which is the number of viruses detected by Lindsley *et al.*⁽⁴⁹⁾ Yang *et al.* detected 16,000 viruses/m³, the high value input, in a health-care facility and reported similar results for child-care facilities and planes.⁽⁵¹⁾ They also reported a concentration of 37,000 viruses/m³ for a childcare facility; however, this value was not used as an input because childcare facilities do not have the ventilation requirements of hospitals. Tseng *et al.* measured influenza concentrations in a pediatric emergency room during flu season.⁽⁵²⁾ The lowest level of virus detected was 168 viruses/m³. It should be noted that those researchers reported a significant correlation between patients with lower respiratory infections and influenza A counts. There were approximately seven patients with lower respiratory infections in the emergency room when the value of 168 viruses/m³ was measured. All C_{out} values were obtained by collecting aerosol samples in emergency departments. Because the C_{out} inputs were reported as concentrations, sampling time differences among the references can be ignored.

Among the four variables in the model, C_{out} is the most sensitive to the user's specific workplace environment. For example, aerosol-generating procedures (such as bronchoscopy, intubation, ventilation, and nebulization) and source control (SM placement on the patient, bedside air filters, etc.) have the potential to significantly increase or decrease levels of airborne respiratory pathogens, respectively.^(15,53–57) Thompson *et al.* reported that bronchoscopies produced exceedingly high levels (284,875 viruses/L) of detected influenza.⁽⁵³⁾ If the value given for C_{out} produced during a bronchoscopy were used in Equation (1), with all other variables kept at their likely level, the estimated FFR contamination would be over 100 million viruses, which is much higher than in any of the typical scenarios modeled in Table IV. Milton *et al.* determined that the use of SMs on patients (source control) produced 25-fold and 2.8-fold reductions in the detected influenza RNA copy number for coarse and fine particles, respectively.⁽⁵⁷⁾ Using a conservative estimate of a 2× reduction in C_{out} because of masking patients would result in a significant reduction to the estimated facemask contamination level. However, additional research is needed before we can confidently apply the models for these scenarios.

The input level for duration of facemask wear had the second largest impact on C_{fa} . For our simulations, we estimated the most likely duration of patient interaction to be 20 minutes, which is supported by multiple literature sources.^(58,59) However, the high-value-input scenario (6.6 hours) is unlikely in practice. An extended length of time of respirator wear is not consistent with the requirements that FFRs be discarded after each patient encounter, except for cases of tuberculosis, where reuse is permitted.⁽³⁾ Most HCWs need to take breaks during the day, and there are very few situations where more than two hours of

continuous wear is likely to occur. The input value we selected for patient interaction in this scenario, 6.6 hours, was based on the findings of Radonovich *et al.* In their study, the purpose was to determine the maximum time a HCW could tolerate an FFR in the event that extended use was required to maintain FFR supplies in periods of high demand.⁽⁶⁰⁾ The value 6.6 was chosen because this was the maximum time that HCWs were able to tolerate an N95 FFR. During this experiment, the HCWs were permitted breaks in which they doffed their FFRs for 15–30 minutes, which would further reduce t .

The input level for inhalation rate had only a small impact on C_{fa} . The inputs for IR_a were selected from ISO/TS 16976-1. This document is intended for the preparation of standards for performance requirements, testing, and use of respiratory protective devices and provides respiratory responses for various metabolic rates associated with mainly industrial activities, as defined in ISO8996. The inputs for IR_a were based on individuals at rest and with light and moderate metabolic rates, which correspond to low, likely, and high input values for the model. The low IR_a is associated with sedentary work, typical of office settings. The likely IR_a value is associated with activities of laboratory assistants and teachers, who (like HCWs) are often standing for long periods of time. The high-value IR_a input is associated with the activities of craftsmen such as brick layers and carpenters but could be achieved by HCWs during activities such as patient lifting. The IR_a values used in the model are based on a person with a weight of 85 kg, which may be higher than the mean weight of the HCW population. Lower IR_a values were reported in the literature for sleeping or resting and therefore were not included in the estimate.

The relatively small range of input values for facemask barrier efficiency used in Table III caused this variable to have the least change in estimated C_{fa} . As expected, the simulations using the aerosol model predict that FFRs capture more viruses than SMs because they provide a tighter seal around the face and contain filter media with higher levels of filtration performance. Although the relative difference between the highest value and low value inputs is minimal, this variable was the most difficult for which to find useful input values. The input values selected for the simulation required careful assumptions, and there are no published data on E_b from actual healthcare settings or that have C_{in} data (i.e., virus concentrations inside the facemask) that can be used directly in Equation (2). Instead, we selected N95 FFR-specific WPF data from other workplace settings for the FFR simulations and laboratory data with human test subjects for the SM simulations. The most likely E_b for FFRs was determined by calculating the median WPF across all of the reported geometric mean WPF values in each study.^(5–9,61) The low value was based on OSHA's minimum required assigned protection factor of 10 for N95 FFRs. The high value input for E_b was determined from the highest WPF (9,100) measured for an FFR wearer in a grinding operation.⁽⁹⁾ All E_b values for SMs were selected from a study by Oberg and Brosseau, who assessed SM performance using quantitative fit tests.⁽¹¹⁾ The average overall fit factor (FF) for SMs donned without assistance represented the most likely E_b of a SM for the model. The low and high values represent the worst and best FFs reported in the Oberg and Brosseau study. A modified version of Equation (2) was used to convert the reported WPF and FF values to E_b (e.g., $E_b = 1 - \frac{1}{WPF \text{ or } FF}$). The likely E_b values selected for FFRs and SMs

were 0.991 and 0.77, respectively, which represent a WPF = 120 and an average FF of 4.4, respectively.

The aerosol and cough models have a variety of potential uses.

- Manufacturers and researchers can use the model to develop better facemasks. Recently, there has been an interest in developing technologies to mediate the fomite hazards of face-masks used in healthcare facilities. The requirement to incorporate such technologies in future standards (for example, Project BREATHE's B95 standard) is being debated. Research has been conducted on facemasks with integrated antimicrobial technology, and the FDA has cleared a few antimicrobial FFRs.^(16,62,63) Research has also examined the efficacy of chemical and energetic methods to decontaminate FFRs. Both integrated antimicrobial technologies and decontamination methods can be tested with use of ASTM E2720-10 and E2721-10, which are aerosol- and droplet-based methods, respectively, designed for use with air-permeable materials such as facemasks. To allow for demonstration of a $3\text{-log}_{10}\text{TCID}_{50}$ efficacy in the reduction of viral contamination, these methods require a viral challenge of $4\text{-log}_{10}\text{TCID}_{50}/\text{cm}$ on the facemask samples. This is equivalent to 200,000 TCID₅₀ on the facemask, which is highly unlikely in typical situations, as determined by the models. Using models to predict facemask contamination would allow manufacturers and researchers to better assess the efficacy and/or cost effectiveness of antimicrobial, chemical, and energetic technologies for facemask decontamination in hospital settings.
- Policymakers can use the models to better understand reaerosolization and fomite hazards resulting from the reuse of influenza-contaminated facemasks. As an example, during the H1N1 pandemic of 2009, FFR reuse and extended use were considered as possible ways to save FFR supplies. Concerns about the safety of such policies were debated. It was speculated that reuse could lead to self-inoculation, transmission to a patient, or contamination of other surfaces such as doorknobs, bedrails, and computers, which could then be picked up by other HCWs or patients.
- And finally, researchers and epidemiologists may be able to use derivatives of the model to characterize contamination levels in hospitals based on the level of facemask contamination (for example, by solving for C_{out} with use of measured values for C_{fa}). It may be possible that facemasks, collected from HCWs and analyzed for the presence of influenza, could provide information about the concentrations of influenza within a healthcare facility and could be used to compare contamination levels on the basis of location within the facility, procedure conducted by the HCW while wearing the facemask, job description, or other aspects of the HCWs and healthcare facilities.

5. LIMITATIONS AND FUTURE STUDIES

The application of the models to estimate facemask contamination is not without limitations. The cough model was not validated by laboratory studies. The aerosol and cough models do not reflect all aspects affecting facemask contamination in the healthcare environment, such

as aerosol concentration variability (resulting from an aerosol-generating procedure or application of some method of source control, for instance), virus viability, user-generated virus particles, or contact contamination from touching the facemask with contaminated gloves or hands. The model does not consider the additive nature of simultaneous direct-spray and aerosol contamination. The model was not validated with data from an actual healthcare facility or with other infectious aerosols. Data for model inputs were limited and may not accurately depict the typical conditions seen in all healthcare facilities.

In the future, we will be analyzing the risks associated with reusing a contaminated facemask and will consider other factors such as virus viability, transfer efficiency, and transport to the targeted cells of the respiratory tract. For example, an estimate of viable virus captured on the facemask at the end of a given facemask wearing period could be calculated using the equation $C_{fa} = (I/\alpha) \times [1 - \exp(-\alpha \times t)]$, where constant capture rate of infectious virus is denoted as I , first-order loss of infectivity is α , and facemask wear duration as t .

6. CONCLUSIONS

In this work, models were used to estimate facemask influenza contamination levels via aerosol deposition for three scenarios and deposition via direct spray (cough). These models suggest that influenza contamination levels from a single cough are much less than contamination levels from aerosol sources. Even for aerosol contamination, wide variation was found in estimated facemask contamination levels, depending on the input values selected. Overall, these models and the estimates for facemask contamination levels can be used to inform current infection control practice and future research related to the development of better facemasks, to characterize airborne contamination levels, and to assist in the assessment of risk from re-aerosolization and fomite transfer from the handling and reuse of contaminated facemasks.

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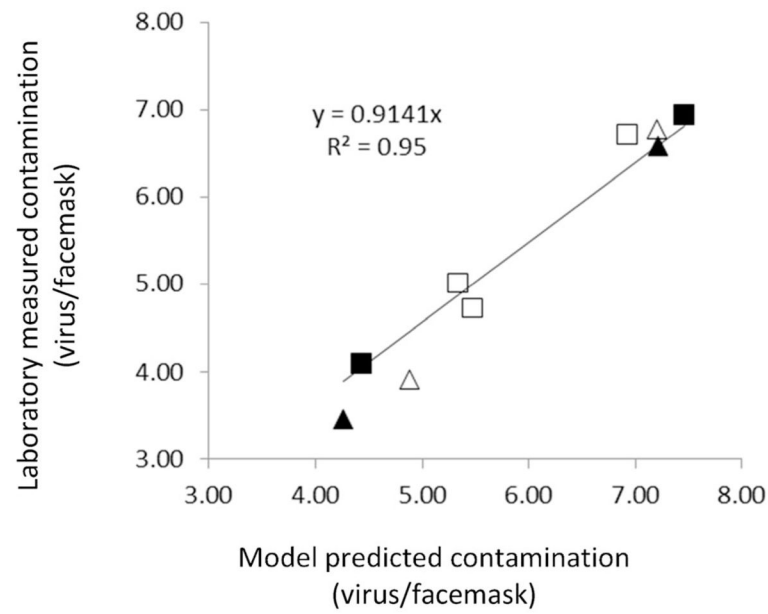
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**Fig. 1.**

Correlation between model predicted contamination and laboratory measured facemask contamination. The squares represent data points for N95 FFRs coupons. The triangles represent data for SMs coupons. Sealed and unsealed configurations of face-mask attachment to the headform are represented as black and white symbols, respectively.

Table I

List of Model Parameters

Parameter	Description	Units
A_{fm}	Area of the facemask	cm ²
C_{fa}	Contamination on the facemask from aerosol exposure	Virus/facemask
C_{fc}	Contamination on the facemask from a cough	Virus/facemask
C_{in}	Concentration of particles inside the facemask	Virus/m ³
C_{out}	Aerosols concentration of virus in the environment (outside of facemask)	Virus/m ³
A_C	Area of a cough	cm ²
E_b	Barrier efficiency of the facemask	–
IR_a	Inhalation rate of facemask user	m ³ /hour
t	Duration of facemask use	Hour
V_c	Viruses in a cough	Viruses

Table II

Validation of the Facemask Contamination from Aerosols Model (Equation (1))

Mask Type/Configuration	# of Replicates	C_{out} (virus/m ³)	IR_a (m ³ /hour)	t (hour)	E_b	Model Predicted $\log C_{fa}$	Measured $\log C_{fa}^c$
Unsealed SM ^a	2	1.30E + 07	1.92	1	0.638	7.20	6.78
Unsealed N95 ^a	3	6.30E + 06	1.92	1	0.695	6.92	6.72
Sealed SM ^a	2	9.00E + 06	1.92	1	0.945	7.21	6.59
Sealed N95 ^a	2	1.50E + 07	1.92	1	0.998	7.46	6.94
Sealed SM ^b	1	1.00E + 04	1.92	1	0.945	4.26	3.46
Sealed N95 ^b	1	1.40E + 04	1.92	1	0.998	4.43	4.10
Unsealed SM ^b	1	6.20E + 04	1.92	1	0.638	4.88	3.92
Unsealed N95 ^b	1	1.63E + 05	1.92	1	0.695	5.34	5.02
Unsealed N95 ^b	1	2.21E + 05	1.92	1	0.695	5.47	4.73

^a C_{out} , IR_a , t , E_b from Noti *et al.* (2012).^b C_{out} , IR_a , t from personal communication. E_b from Noti *et al.* (2012).^c Virus counts from facemask samples were multiplied by 40, the ratio of full facemask to sampled (coupon) surface area.

Table III

Data from Selected References Used to Derive Input Values

First Author or Document No.	Year	C_{init} (virus/m ³)	IR_a (m ³ /hour)	E_b	t (hour)
Janssen	2007			0.80–0.999	
Janssen	2007			0.958–0.999	
Bidwell	2004			0.916–0.999	
Han	2002			0.80–0.995	
Cho	2011			0.928–0.993	
Cho	2010			0.985–0.999	
29cfr1910.134	2009			0.90	
Oberg	2008			0.60–0.90	
Radonovich	2009				6.6
Detmar	2002				0.33
Epstein	2005				0.33
Flocke	2002				0.16
Gottschalk	2005				0.16
Tseng	2010	168–5,020			
Yang	2011	5,800–16,000			
Lindsley	2010	12,000			
Lindsley	2012	355			
Lee	2004		0.9		
Grinshpun	2009		0.9–1.92		
ISO/TS 16976-1	2007		0.78, 1.14, 1.92		

Table IV

Model Predicted Facemask Contamination from Aerosols

Facemask Type	Scenario	C _{out} (Virus/m ³)	IR _a (m ³ /hour)	E _b	t (hour)	C _{fa}
FFR	Low	168	0.780	0.900	0.160	19
	High	16,000	1.920	0.999	6.600	202,549
	Likely	12,000	1.140	0.991	0.330	4,473
SM	Low	168	0.780	0.600	0.160	13
	High	16,000	1.920	0.900	6.600	182,477
	Likely	12,000	1.140	0.770	0.330	3,476

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Table V

Model Predicted Facemask Contamination from Coughs

Facemask	Scenario	V_c (Virus/cough)	A_{fm} (cm ²)	A_c	(cm ²)	C_{fc}
FFR/SM	Cough	355	200	3,800		19